The future of neutrino physics

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- Overview
- Unanswered neutrino questions
- Areas of neutrino research
- Ranking and Conclusion

Overview

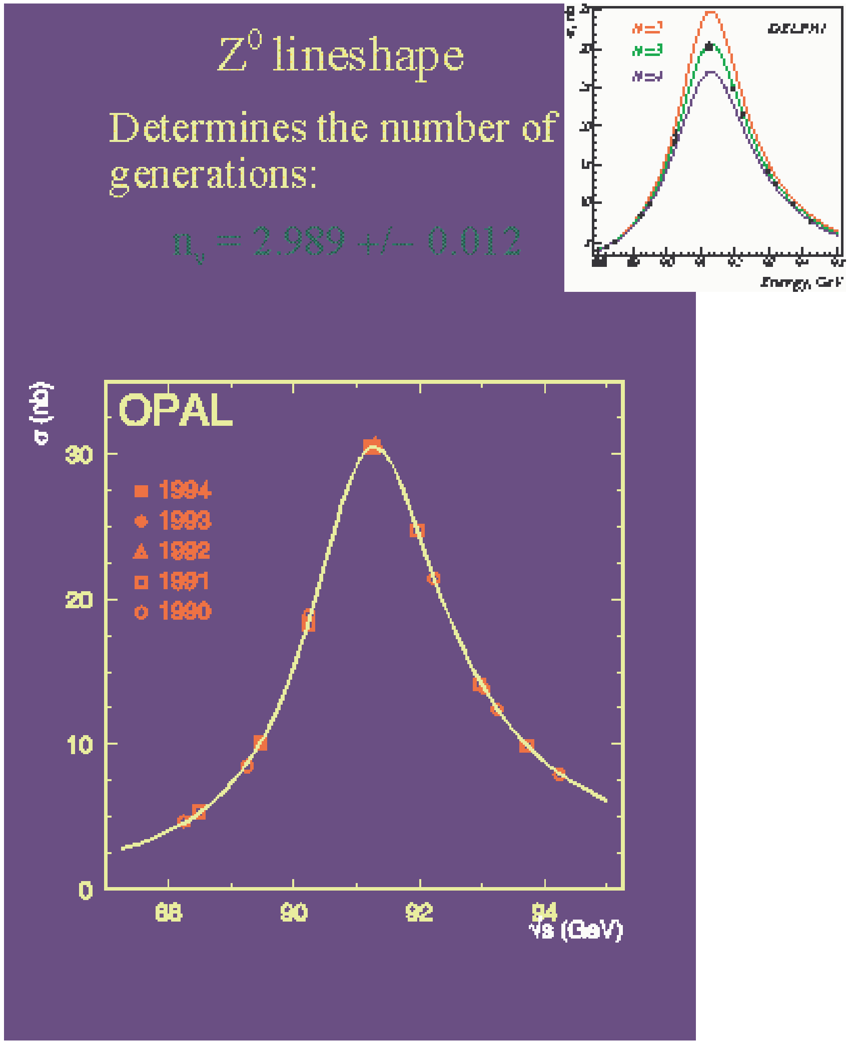
- This class has spent 1 semester researching the different areas of neutrino physics
- In our final class, we discussed the major questions in neutrino physics we encountered and which experiments we think are most important
- Here’s what we’ve learned and our thoughts for the future…

Unanswered questions: fundamental

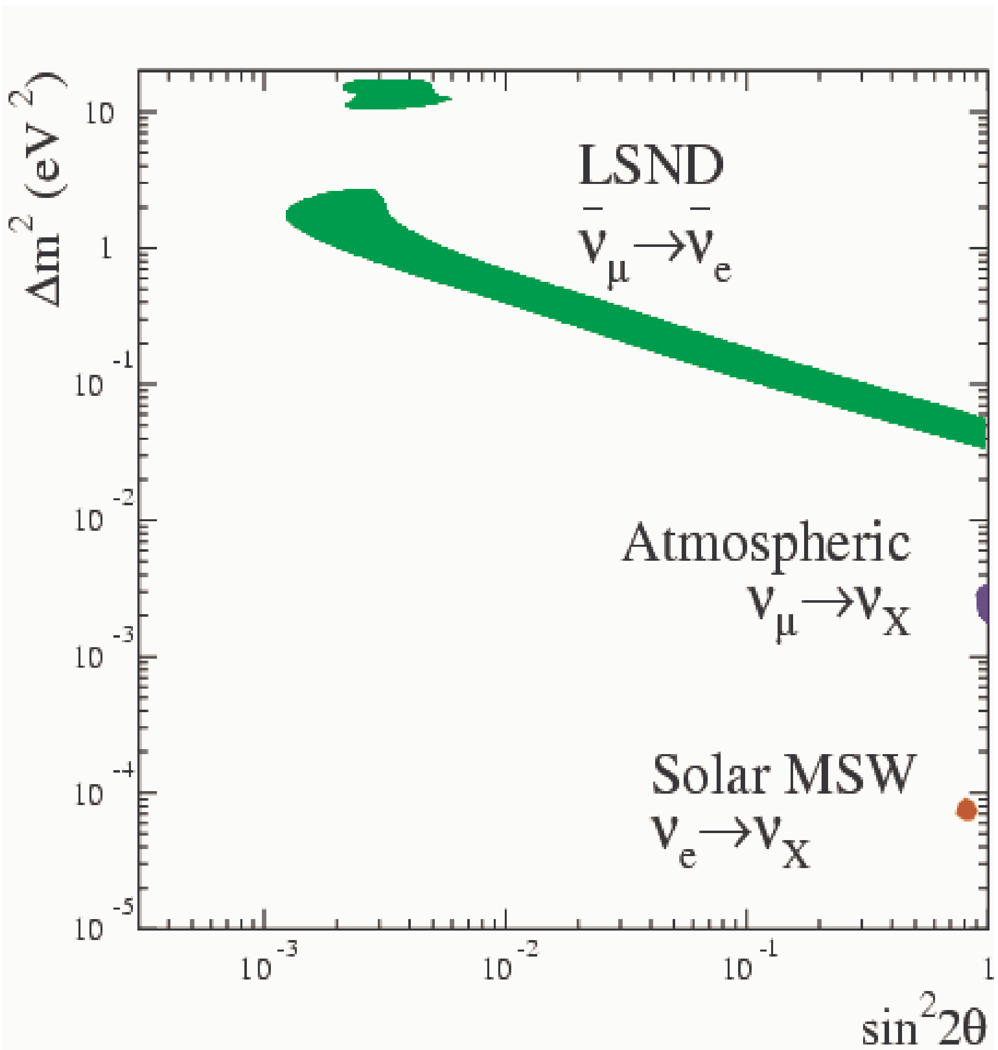
1. How many neutrino species? Are there sterile ν?
2. Scale of neutrino mass and mass hierarchy
3. What is the neutrino mass/mixing matrix? Why is it so different from quarks?
4. CP violation in neutrino sector? Leptogenesis?
5. Dirac neutrinos? Majorana neutrinos?

Kinds of neutrinos

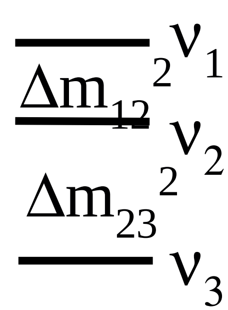
- Exp'ts at LEP show only 3 active flavors with mass < 45 GeV (from decay of the Z boson)
- They are all left handed
- Most Grand Unified Theories (GUTs) have extra particles which mix with the neutrino
  - It's hard to build just a left handed one, especially if it's massive



Sterile neutrinos



- There are too many Δm^2's for three neutrinos



$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

- Non-interacting "sterile" neutrinos?

Scale of neutrino mass and mass hierarchy

- Currently, we know $\nu \sim < 1\text{eV}$
- We have a lower limit on square root of Δm^2
- The electron (m_e=.511 MeV) is ~500,000 times bigger than the neutrinos, why?
- What is the order of the mass eigenstates? Is there an overall offset?

ν_3 ______ ← Like quarks? ν_3 ______

Δm_{23}^2 ν_2 ______ Δm_{23}^2

ν_2 ______ Not like quarks? → Δm_{12}^2

Δm_{12}^2

ν_1 ______ ν_1 ______

Neutrino mass/mixing matrix

CP phase δ

BIG

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- All terms are big, except for $U_{e3}=\sin\theta_{13}\, e^{i\delta}$; how small is θ_{13}?
  - θ_{13} is mixing angle, δ is possibly CP violating phase
- Quark matrix is big only on diagonal

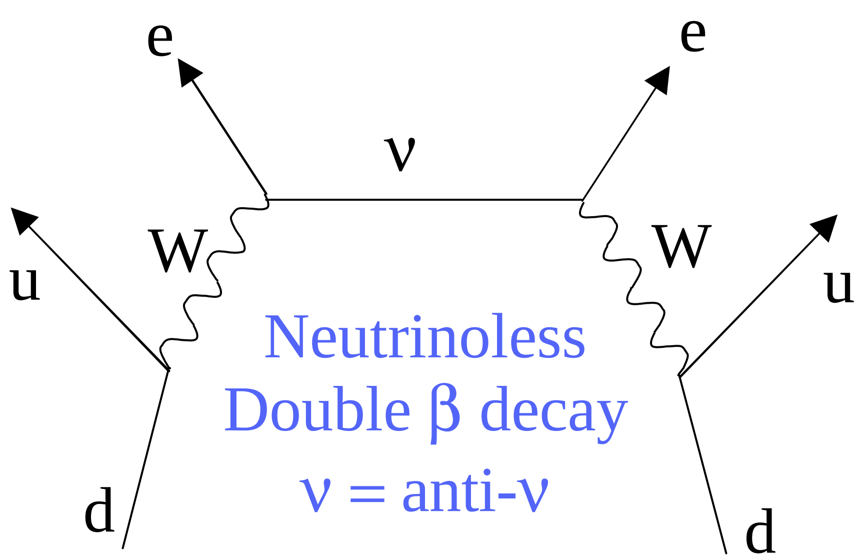
CP violation?

- A symmetry just means nature does not distinguish
  - C: charge, $\nu \rightarrow$ anti-ν
  - P: parity, $\nu_{Left} \rightarrow \nu_{Right}$
- CP violation in neutrinos would mean that the probability of oscillation for neutrinos is different than anti-neutrinos
- CP violation in leptons could be a reason why we see matter/antimatter asymmetry in the universe
  - Leptogenesis (Boris, care to elaborate?)
- CPT violation would mean the mass hierarchy of neutrinos would be different from anti-neutrinos

Majorana neutrinos

- The difference between particle & antiparticle is usually electric charge. (particles move one way in a B-field, antiparticles the other)

- But neutrinos have no charge with which we can tell a difference If neutrinos are Majorana particles, then neutrinos are their own antiparticles, and, in principle, they can annihilate...



Majorana neutrinos are a feature of a lot of GUTs

Unanswered questions: in astrophysics

Use neutrinos to as probes of universe:

6. High energy neutrino physics
   - Origin of highest energy cosmic rays?
   - New (TeV scale) physics?
7. Find new astrophysical sources (e.g AGN)
8. Learn more about supernova (DSNB)
9. See early universe with relic ν (CNB)
   - At the moment, no experiment. Ideas?

Areas of neutrino research

- Solar neutrinos
- Atmospheric neutrinos
- Long Baseline experiments
- Short Baseline experiments
- Reactor neutrinos
- Neutrino-less beta decay
- Neutrinos from space
- Neutrino factory (R&D)

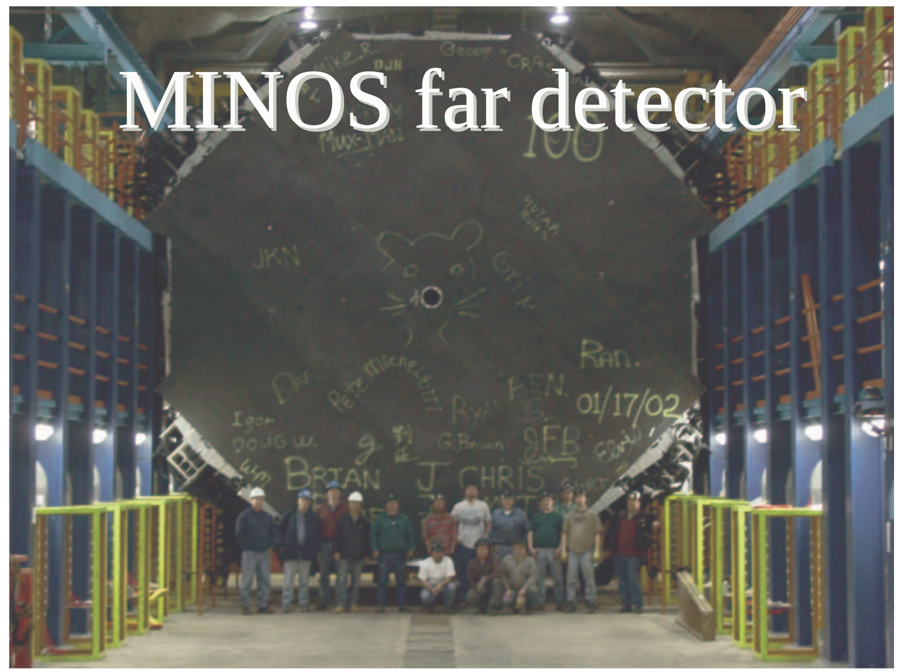
Detection

- Neutrino enters detector, interacts and a charged particle leaves
  - Indirectly observe neutrino by
    1. Calorimeter detectors
    2. Cerenkov light
    3. Radiochemical detectors
    4. Liquid Argon/noble gas detectors

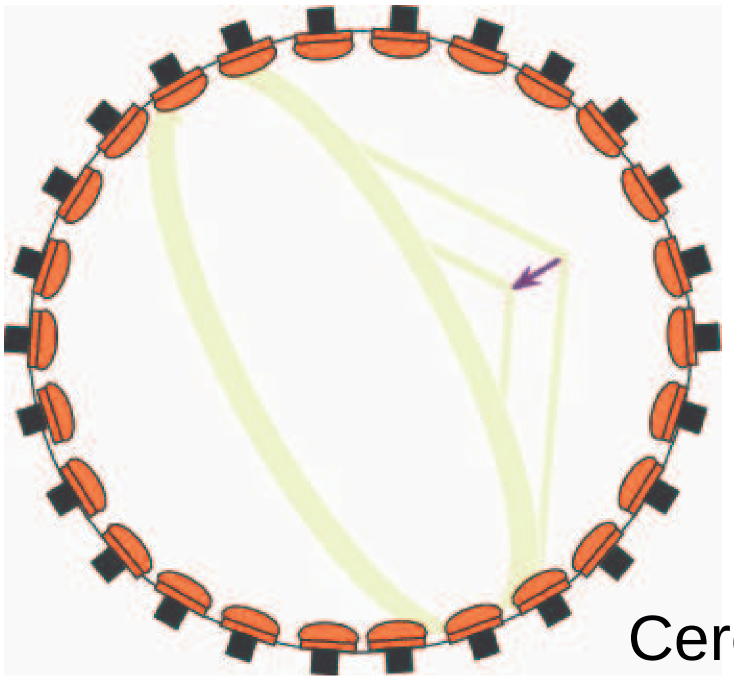
Calorimeter Detectors

•Consists of slabs of “target” material (steel, in MINOS) alternated with “active” material (like solid scintillator and fibers)

• Neutrino enters, interacts in target, interaction products (like muon or electron) are read out by active material



Cerenkov Detector



•Neutrino interacts in tank (filled with oil, liquid scintillator, water or heavy water)

•Charged particle moving faster than the speed of light in that medium produces a “light boom”, which is read out by PMTs

Radiochemical detectors

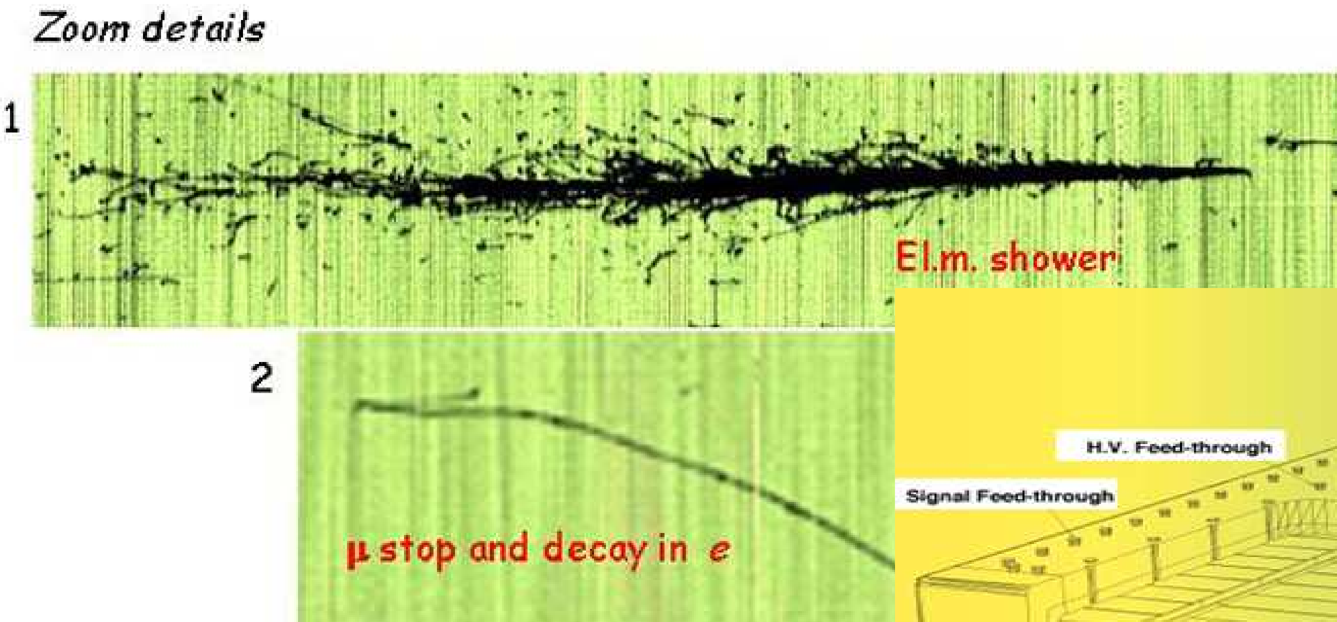
•Detector is filled with a chemical (Homestake contained Cl)

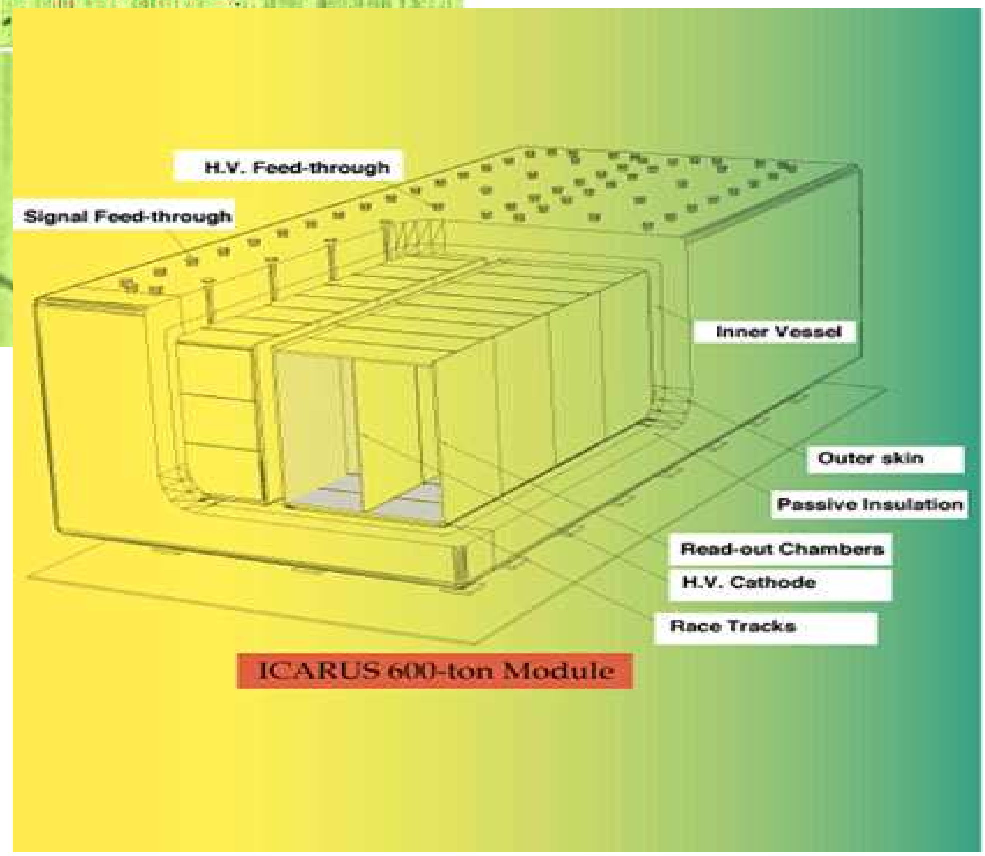
•Neutrino interacts and changes Cl into Ar:

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

•After some period of time, the atoms that interacted with the neutrinos are collected (via "bubbling" gas in tank) and counted

Liquid Argon TPC





- Passing charged particles produce ionization electrons
- Electrons drift to wire planes
- Has very good resolution

Solar neutrinos

Electron neutrinos come from different reactions in the sun

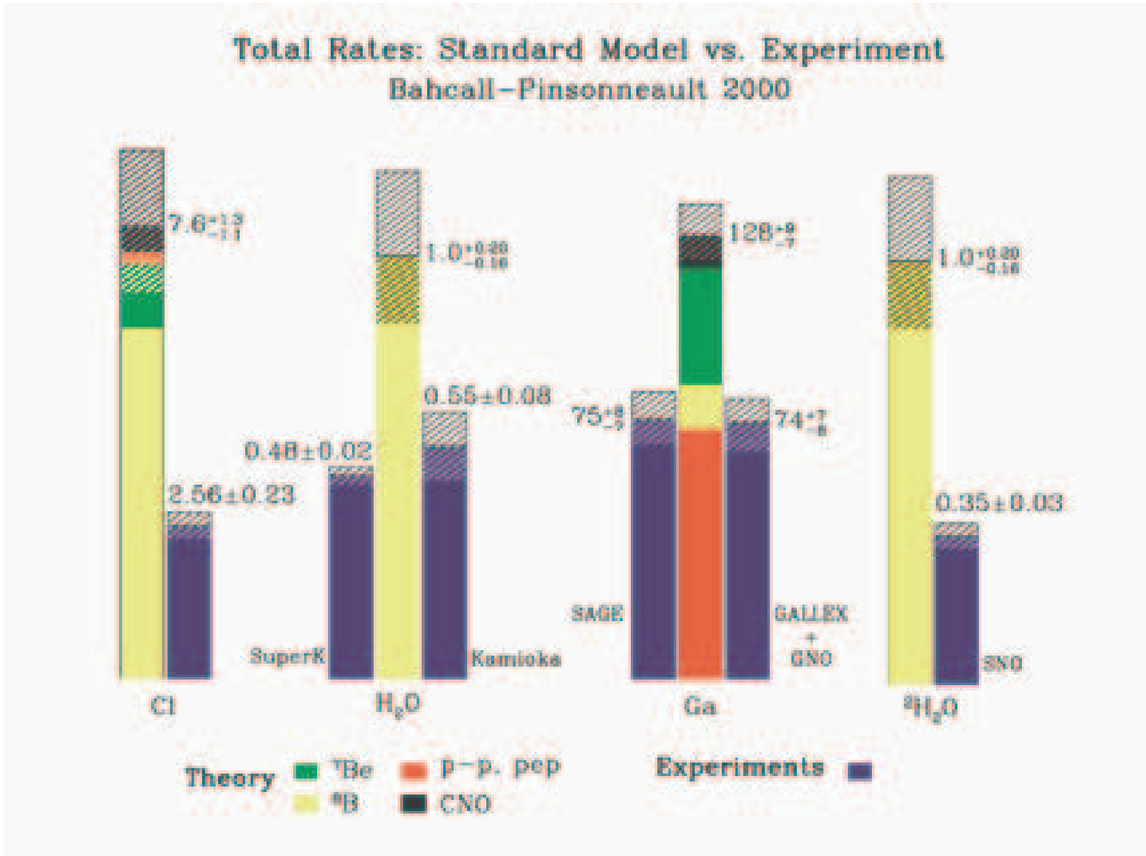
- Mainly from pp "chains"

  $p + p \rightarrow H + e^+ + \nu_e$ and $Be + e^- \rightarrow Li + \nu_e$
- Are of typical energies of ~1-10 MeV

These are measured by a host of experiments:

Homestake, SAGE, GALLEX, Super-Kamiokande (Super-K) and most notably, SNO.

Solar neutrinos



•Only ~1/3-2/3 of the expected ν_e are observed

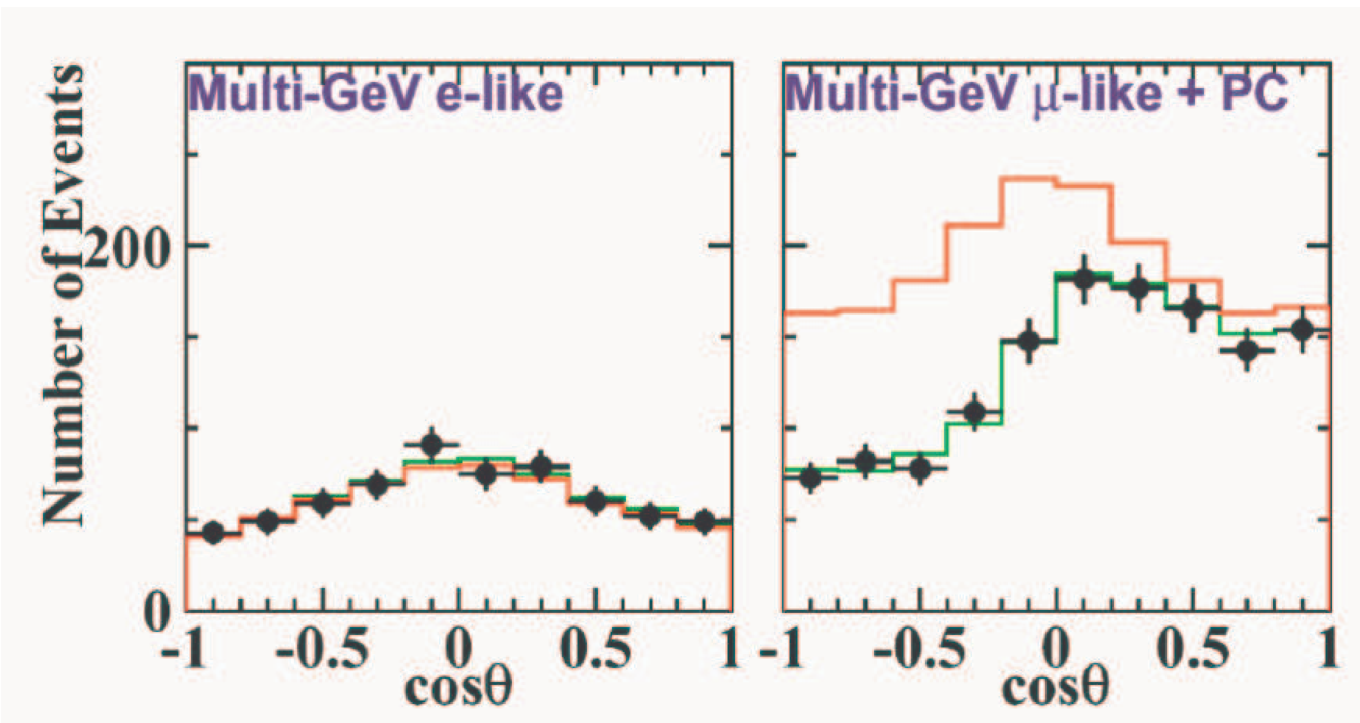
•Is this oscillation? Yes! SNO confirmed ν_e flux, Kamland reproduced effect with reactor ν_e

Atmospheric neutrinos

ν are also produced in the atmosphere (<100 MeV)

$p + N \rightarrow \pi \rightarrow \mu + \nu_\mu$

$\mu \rightarrow \nu_\mu + e^- + \nu_e$ $\rightarrow$ Expect 2 ν_μ to 1 ν_e



Super-K sees a deficit of ν_μ and expected ν_e ; oscillation!?

Oscillation!!

- We now have an answer for the solar neutrino and the atmospheric problem… but now we have more questions
- Solar and atmospheric neutrino physics have opened the door for current accelerator neutrino physics (short and long baseline experiments)

Long Baseline Experiments

- Accelerators produce 1-20 GeV ν_μ that are seen at a distant (250km-733km) detector
- Measures oscillations at atmospheric $L/E \sim 1/\Delta m^2$
- Currently, K2K, MINOS and soon CNGS, JPARC
- Future experiments include
  - off axis beams (narrower ν energy spread, but lose rate)
  - superbeams (low E, high intensity beams with less background of ν_e off axis)

Long Baseline Exp'ts (cont'd)

- Has great physics potential (CP violation, mass hierarchy, mixing matrix)
- Accelerator is reusable for future exp'ts
- Costly in time (~8 years) and money (min ~500 million US$) if better than existing exp'ts
- Depends on θ_{13} and accelerators p.o.t.

➢ Wait for reactor experiments to establish θ_{13} and do useful R&D/planning till then

If θ_{13} is small, Liquid argon detector might be needed

Short Baseline Experiments

- Similar physics to long baseline exp'ts, just look at a different L/E or $1/\Delta m^2$
- MiniBooNE
  - Third Δm^2 observed by LSND needs to be confirmed or disproved
- HARP
  - Better measurement of pion cross section for neutrino production at different energies
- MINErVA and FINeSSE
  - Additional detectors for MINOS and MiniBooNE
  - improves particle ID, measure n cross section, increase understanding of backgrounds and improves oscillation results

Short Baseline Experiments

- Possible CPT violation (no signal in ν, signal in anti-ν) and sterile ν (signal in ν)
- Establishes not well known ν cross sections
- MINErVA and FINeSSE improve results their parent experiment
- All are cheap (~4-6 million US$)

➢ Provides important checks and information for future exp’ts

Reactor Experiments

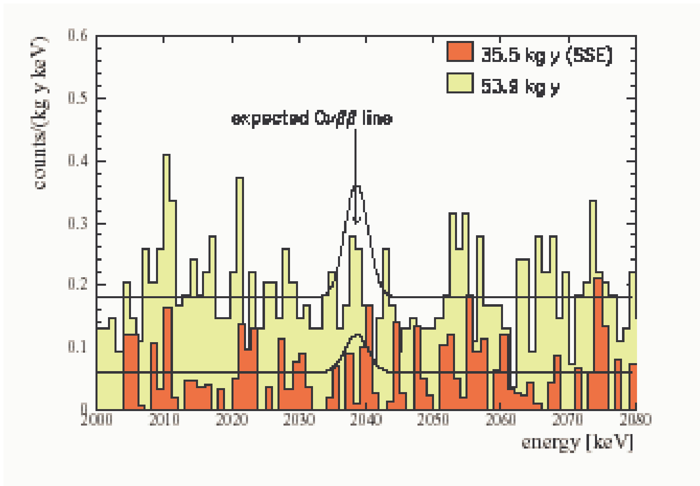
- Nearby detectors observe isotropic anti-ν_e from reactors (~1-10MeV)
- Measure not-well-known mixing angle (θ_{13})
- Expt's include
  - Kamland (solar Δm^2)
  - Paulo Verde and CHOOZ (atm Δm^2)
  - Unnamed future exp'ts
- Cheap (~25-50 mil US$) but not reusable detectors
- Provides important measurement of θ_{13} (If θ_{13} too small, then can't measure with long baseline exp't)

➢ Important to do now and do fast

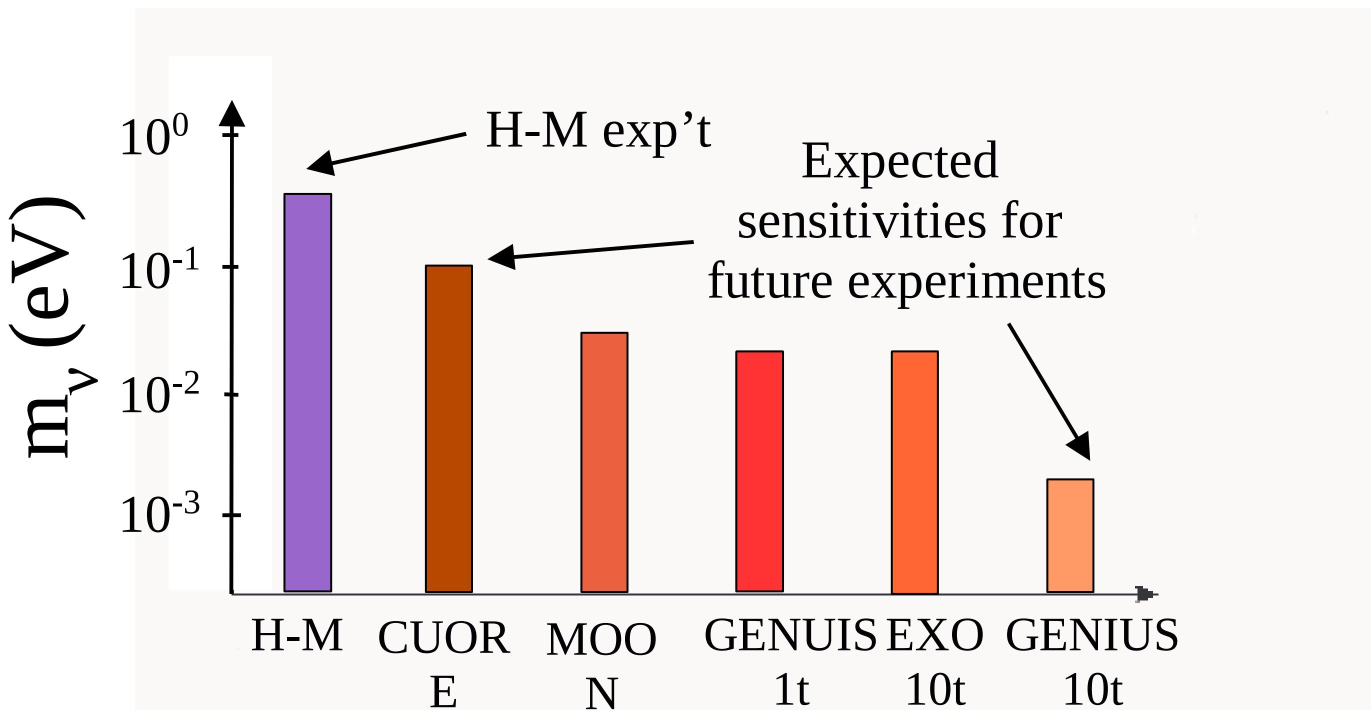
Neutrinoless beta decay (0νββ)

- Large, very sensitive detector sits underground and waits for such a decay
  - Backgrounds are from 2νββ rate, and especially any radioactive material
- Current expt's:
  - Heidelburg-Moscow ran for ~10 yrs, claims detection… but has not convinced the community
- Future expt's:
  - EXO, GENIUS, MAJORANA, and more!

Neutrinoless double beta decay



•Klapdor-Kleingrothaus et al released a paper in 2001 claiming that they had detected neutrinoless double beta decay, based on this graph



$0\nu\beta\beta$

- Can establish if ν is Dirac or Majorana (essential in most GUTs)
- Detectors are large, expensive and have difficult backgrounds
- Feasibilty of this measurement has not been well established

➢ Investigate first
  - if it is proven it works and isn't too expensive then fund

Neutrino astrophysics

- AMANDA/IceCUBE
  - Giant Cerenkov detector in Antarctic ice
  - acts as a “neutrino telescope”
- SNEWS
  - Network of neutrino detectors around the world
  - Directs astronomers to supernovae early using neutrinos that come before light does
- GADZOOKS
  - Stands for: Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!
  - Dump $GdCl_3$ into Super-K to improve observational capabilities of supernova ν

Neutrino astrophysics (cont'd)

- Vast possibilities in astrophysics
  - Supernovae (DSNB and early detection)
  - origin of highest energy cosmic rays
  - AGNs and other exotic sources
- Risky
  - what if there is no supernova? no new physics?
- Relatively cheap for potential
  - IceCube ~100 million US$, other much less ~500,000$)
- ➢ Worth it in short term
  - Provided $GdCl_3$ is safe in Super-K (and GADZOOKS changes the name)

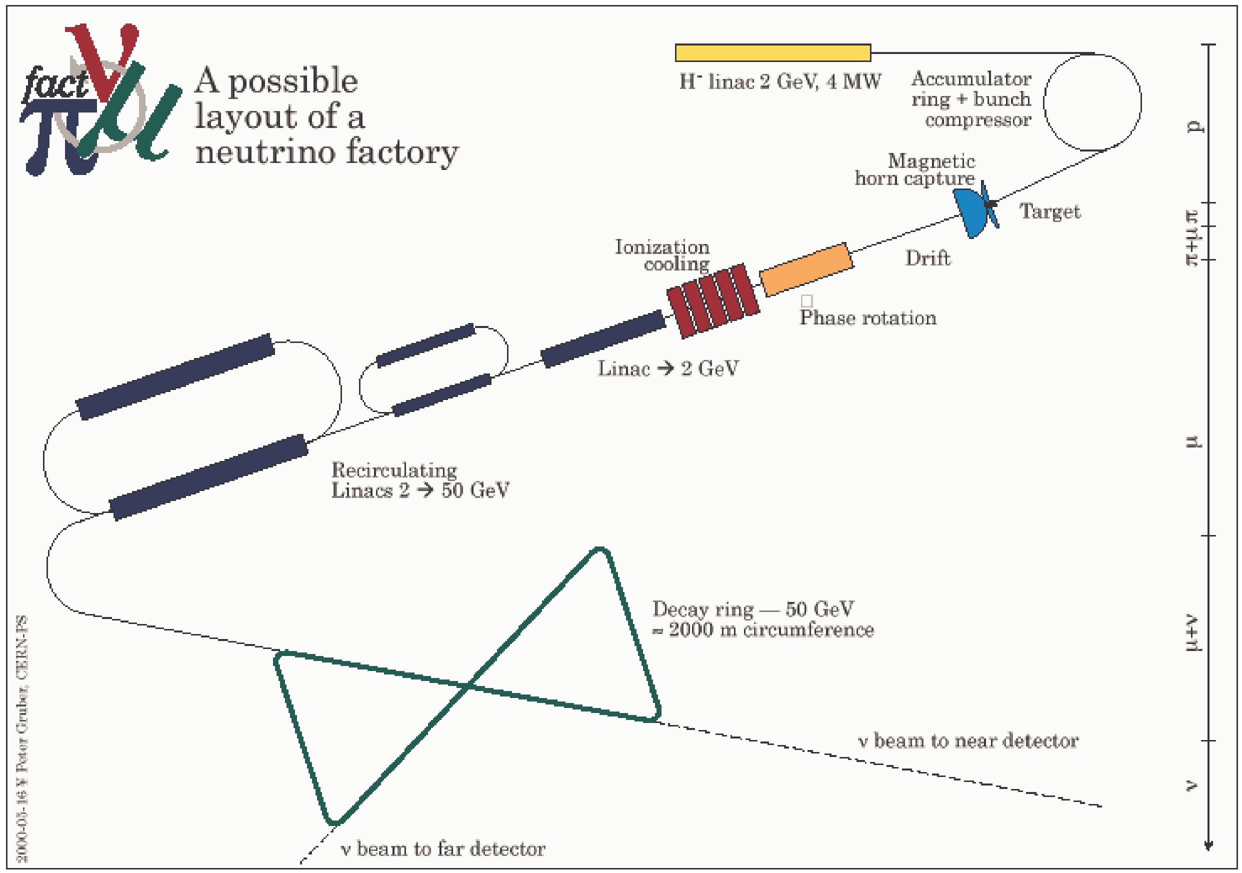
Neutrino factory

Intense proton source produces pions which decay to muons

The muons are bunched, cooled and put in rings

and decay to neutrinos

=> Intense neutrino source!



Neutrino factory

- Has the ability to answer many of the outstanding questions with high ν fluxes
- Other (non-ν) physics uses (muon colliders)
- But we can't build one yet!
  - Current R&D projects are MICE and MUCOOL
  - Difficulties in controling a muon beam
    - Hard to cool muons, they decay quickly
    - Muons are difficult to collimate

➢ Long term goal: continue R&D

Ranking and Conclusion

- Atmospheric and solar sector have paved the way for current experiments
- Funding to:
  I. Reactors
  II. Astrophysics projects
  III. Short-baseline experiments
  IV. R&D on (useful) long baseline technology
- Investigate neutrino-less beta decay
- For the long term, invest in neutrino factories

Choices (I)

- Reactors
  - Knowing θ_{13} gives the long baseline experiments important information in designing the next generation project (500 million with the wrong detector?)
- Astrophysics projects
  I. SNEWS and GADZOOKS provide more information on supernovae, and are very cheap
  II. IceCUBE is not cheap, but we can’t explore TeV scale on earth for that price

Choices (II)

- Short Baseline
  I. Cheap and improved (or new) physics
  II. Close (or open) doors on LSND
- R&D on long baseline technology
  I. Liquid Argon detectors are the next kind of detectors, worth research
  II. Any long term project is always worth taking time to think out

Choices (III)

- Investigate neutrino-less beta decay
  - Important physics question, but is experiment possible?
- For the long term, invest in neutrino factories
  - Next generation for not only neutrinos, but colliders in general

Timeline

Now	Near future	Far future
Reactors	Long baseline	Neutrino Factories
Short baseline	$0\nu\beta\beta$?	
ν Astrophysics		
R&D on LBL		